HYPERQUADRATIC POWER SERIES IN $\mathbb{F}_3((T^{-1}))$ WITH PARTIAL QUOTIENTS OF DEGREE 1

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Abstract. In this note we describe a large family of nonquadratic continued fractions in the field $\mathbb{F}_3((T^{-1}))$ of power series over the finite field $\mathbb{F}_3$. These continued fractions are remarkable for two reasons : they satisfy an algebraic equation with coefficient in $\mathbb{F}_3[T]$, explicitly given, and all the partial quotients in the expansion are polynomials of degree 1. In 1986, in a basic article in this area of research [MR], Mills and Robbins gave the first example of an element belonging to this family.

1. Introduction

We are concerned with power series in $1/T$ over a finite field, where T is an indeterminate. If the base field is $\mathbb{F}_q$, the finite field of characteristic p with q elements, these power series belong to the field $\mathbb{F}_q((T^{-1}))$, which will be here denoted by $\mathbb{F}(q)$. Thus a nonzero element of $\mathbb{F}(q)$ is represented by

$$\alpha = \sum_{k \leq k_0} u_k T^k \quad \text{where } k_0 \in \mathbb{Z}, u_k \in \mathbb{F}_q \quad \text{and } u_{k_0} \neq 0.$$

An absolute value on this field is defined by $|\alpha| = |T|^{k_0}$ where $|T| > 1$ is a fixed real number. We also denote by $\mathbb{F}(q)^+$ the subset of power series α such that $|\alpha| > 1$. We know that each irrational element $\alpha \in \mathbb{F}(q)^+$ can be expanded as an infinite continued fraction. This is denoted

$$\alpha = [a_1, a_2, \dots, a_n, \dots] \quad \text{where } a_i \in \mathbb{F}_q[T] \text{ and } \deg(a_i) > 0 \text{ for } i \geq 1.$$

By truncating this expansion we obtain a rational element, called a convergent to α and denoted by x_n/y_n for $n \geq 1$. The polynomials $(x_n)_{n\geq 0}$ and $(y_n)_{n\geq 0}$, called continuants, are both defined by the same recursion formula: $K_n = a_n K_{n-1} + K_{n-2}$ for $n \geq 2$, with the initial conditions $x_0 = 1$ and $x_1 = a_1$ or $y_0 = 0$ and $y_1 = 1$. The polynomials a_i are called the partial quotients of the expansion. For $n \geq 1$, we

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denote $\alpha_{n+1} = [a_{n+1}, a_{n+2}, \dots]$, called the complete quotient, and we have

$$\alpha = [a_1, a_2, \dots, a_n, \alpha_{n+1}] = (x_n\alpha_{n+1} + x_{n-1})/(y_n\alpha_{n+1} + y_{n-1}).$$

The reader may consult [S] for a general account on continued fractions in power series fields and also [T] for a wider presentation of diophantine approximation in function fields and more references.

In 1986 [MR], Mills and Robbins, developing the pioneer work by Baum and Sweet [BS], introduced a particular subset of algebraic power series. These power series are irrational elements $\alpha \in \mathbb{F}(q)$ satisfying an equation $\alpha = f(\alpha^r)$ where r is a power of the characteristic p of the base field and f is a linear fractional transformation with integer (polynomials in $\mathbb{F}_q[T]$) coefficients. The subset of such elements is denoted by $\mathbb{H}_r(q)$ and its elements are called hyperquadratic.

Throughout this note the base field is $\mathbb{F}_3$, i.e. $q = 3$. We are concerned with elements in $\mathbb{H}_3(3)$ which are not quadratic and have all partial quotients of degree 1 in their continued fraction expansion. A first example of such power series appeared in [MR, p. 401-402].

2. Results

In [L1] the second named author of this note investigated the existence of elements in $\mathbb{H}_3(3)$ with all partial quotients of degree 1. The theorem which we present here is an extended version of the one presented there [L1]. However the proof given here is based on a different method. This method used to obtain other continued fraction expansions of hyperquadratic power series was developed in [L2]. We have the following:

Theorem 1. *Let $m \in \mathbb{N}^*$, $\boldsymbol{\eta} = (\eta_1, \eta_2, \dots, \eta_m) \in (\mathbb{F}_3^*)^m$ where $\eta_m = (-1)^{m-1}$ and $\mathbf{k}= (k_1, k_2, \dots, k_m) \in \mathbb{N}^m$ where $k_1 \geq 2$ and $k_{i+1} - k_i \geq 2$ for $i = 1, \dots, m-1$. We define the following integers,*

$$t_{i,n} = k_m(3^n - 1)/2 + k_i 3^n \quad \textit{for} \quad 1 \leq i \leq m \quad \textit{and} \quad n \geq 0.$$

We observe that we have $t_{i,n} < t_{i+1,n}$ for all (i, n) and $t_{m,n} < t_{1,n+1}$. Also $t_{i,n} \neq t_{j,n'} + 1$. Accordingly, we can define two sequences $(\lambda_t)_{t\geq1}$ and $(\mu_t)_{t\geq1}$ in $\mathbb{F}_3$. For $n \geq 0$, we have

$$\lambda_t = \begin{cases} 1 & \textit{if} \quad 1 \leq t \leq t_{1,0}, \\ (-1)^{mn+i} & \textit{if} \quad t_{i,n} < t \leq t_{i+1,n} \quad \textit{for } 1 \leq i < m, \\ (-1)^{m(n+1)} & \textit{if} \quad t_{m,n} < t \leq t_{1,n+1}. \end{cases}$$

Also $\mu_1 = 1$ *and for* $n \geq 0$, $1 \leq i \leq m$ *and* $t > 1$

$$\mu_t = \begin{cases} (-1)^{n(m+1)}\eta_i & \text{if } t = t_{i,n} \text{ or } t = t_{i,n}+1, \\ 0 & \text{otherwise.} \end{cases}$$

Let $\omega(m, \boldsymbol{\eta}, \mathbf{k}) \in \mathbb{F}(3)$ *be defined by the infinite continued fraction expansion*

$$\omega(m, \boldsymbol{\eta}, \mathbf{k}) = [a_1, a_2, \dots, a_n, \dots] \quad \text{where} \quad a_n = \lambda_n T + \mu_n \quad \text{for } n \geq 1.$$

We consider the two usual sequences $(x_n)_{n\geq 1}$ *and* $(y_n)_{n\geq 1}$ *as being the numerators and denominators of the convergents to* $\omega(m, \boldsymbol{\eta}, \mathbf{k})$.
Then $\omega(m, \boldsymbol{\eta}, \mathbf{k})$ *is the unique root in* $\mathbb{F}(3)^+$ *of the quartic equation*

$$X = \frac{x_l X^3 + (-1)^{m-1} x_{l-3}}{y_l X^3 + (-1)^{m-1} y_{l-3}},$$

where $l = 1 + k_m$.

Remark. *The case* $m = 1$ *and thus* $\boldsymbol{\eta} = (1)$, $\mathbf{k} = (k_1)$, *of this theorem is proved in* [L1]. *The case* $m = 2$, $\boldsymbol{\eta} = (-1, -1)$ *and* $\mathbf{k} = (3, 6)$ *corresponds to the example introduced by Mills and Robbins* [MR].

The generality of this theorem is underlined by the following conjecture, based on extensive computer checking.

Conjecture. *Let* $\alpha \in \mathbb{H}_3(3)$ *be an element which is not quadratic; then* α *has all its partial quotients of degree 1, except for the first ones, if and only if there exist a linear fractional transformation* f, *with coefficients in* $\mathbb{F}_3[T]$ *and determinant in* $\mathbb{F}_3^*$, *a triple* $(m, \boldsymbol{\eta}, \mathbf{k})$ *and a pair* $(\lambda, \mu) \in \mathbb{F}_3^* \times \mathbb{F}_3$ *such that* $\alpha(T) = f(\omega(m, \boldsymbol{\eta}, \mathbf{k})(\lambda T + \mu))$.

3. Proofs

The proof of the theorem stated above will be divided into three steps.

• *First step of the proof:* According to [L2, Theorem 1, p. 332], there exists a unique infinite continued fraction $\beta = [a_1, \dots, a_l, \beta_{l+1}] \in \mathbb{F}(3)$, satisfying

$$\beta^3 = (-1)^m (T^2+1)\beta_{l+1} + T + 1 \quad \text{and} \quad a_i = \lambda_i T + \mu_i, \text{ for } 1 \leq i \leq l,$$

where λ_i, μ_i are the elements defined in the theorem. We know that this element is hyperquadratic and that it is the unique root in $\mathbb{F}(3)^+$ of the algebraic equation $X = (x_l X^3 + B)/(y_l X^3 + D)$ where

$$B = (-1)^m (T^2+1) x_{l-1} - (T+1) x_l \quad \text{and} \quad D = (-1)^m (T^2+1) y_{l-1} - (T+1) y_l.$$

We need to transform B and D. Using the recursive formulas for the continuants, we can write

$$K_{l-3} = (a_l a_{l-1} + 1)K_{l-1} - a_{l-1}K_l. \tag{1}$$

The l first partial quotients of β are given, from the hypothesis of the theorem, and we have

$$a_{l-1} = (-1)^{m-1}(T+1) \quad \text{and} \quad a_l = (-1)^{m-1}(-T+1). \tag{2}$$

Combining (1), applied to both sequences x and y, and (2), we get

$$B = (-1)^{m-1}x_{l-3} \quad \text{and} \quad D = (-1)^{m-1}y_{l-3}.$$

Hence we see that β is the unique root in $\mathbb{F}(3)^+$ of the quartic equation stated in the theorem.

• *Second step of the proof:* In this section $l \geq 1$ is a given integer. We consider all the infinite continued fractions $\alpha \in \mathbb{F}(3)$ defined by $\alpha = [a_1, \dots, a_l, \alpha_{l+1}]$ where $\alpha_{l+1} \in \mathbb{F}(3)$ and

$$a_i = \lambda_i T + \mu_i \quad \text{with} \quad (\lambda_i, \mu_i) \in \mathbb{F}_3^* \times \mathbb{F}_3, \quad \text{for} \quad 1 \leq i \leq l \text{ and} \tag{3}$$

$$\alpha^3 = \epsilon(T^2+1)\alpha_{l+1} + \epsilon' T + \nu_0 \quad \text{with} \quad (\epsilon, \epsilon', \nu_0) \in \mathbb{F}_3^* \times \mathbb{F}_3^* \times \mathbb{F}_3. \tag{4}$$

See [L2, Theorem 1, p. 332], for the existence and unicity of $\alpha \in \mathbb{F}(3)$ defined by the above relations. Our aim is to show that these continued fraction expansions can be explicitly described, under particular conditions on the parameters $(\lambda_i, \mu_i)_{1 \leq i \leq l}$ and $(\epsilon, \epsilon', \nu_0)$. Following the same method as in [L2], we first prove:

Lemma 2. *Let $(\lambda, \epsilon, \epsilon') \in (\mathbb{F}_3^*)^3$ and $\nu \in \mathbb{F}_3$. We set $U = \lambda T^3 - \epsilon' T + \nu$, and $V = \epsilon(T^2+1)$. We set $\delta = \lambda + \epsilon'$ and we assume that $\delta \neq 0$. We define $\epsilon^* = 1$ if $\nu = 0$ and $\epsilon^* = -1$ if $\nu \neq 0$. Then the continued fraction expansion for U/V is given by*

$$U/V = [\epsilon\lambda T, -\epsilon(\delta T + \nu), -\epsilon(\epsilon^*\delta T + \nu)].$$

Moreover, setting $U/V = [u_1, u_2, u_3]$, then for $X \in \mathbb{F}(3)$ we have

$$[U/V, X] = [u_1, u_2, u_3, \frac{X}{(T^2+1)^2} + \frac{\epsilon^*\epsilon(\delta T + \nu)}{T^2+1}].$$

Proof. Since $\epsilon^2 = 1$ and $\delta^2 = 1$, we can write

$$U = \epsilon\lambda T V - \delta T + \nu \quad \text{and} \quad V = \epsilon(\delta T + \nu)(\delta T - \nu) + \epsilon(1 + \nu^2). \tag{5}$$

Clearly (5) implies the following continued fraction expansion

$$U/V = [\epsilon\lambda T, -\epsilon(\delta T + \nu), \epsilon(1+\nu^2)(-\delta T + \nu)]. \tag{6}$$

Finally, observing that $\epsilon(1+\nu^2)=\epsilon^*\epsilon$ and $\epsilon^*\epsilon\nu=-\epsilon\nu$, we see that (6) is the expansion stated in the lemma. The last formula is obtained from [L2, Lemma 3.1 p. 336]. According to this lemma, we have

$$[U/V,X]=[u_1,u_2,u_3,X'] \quad \text{where} \quad X'=X(u_2u_3+1)^{-2}-u_2(u_2u_3+1)^{-1}.$$

We check that $u_2u_3=T^2$ if $\nu=0$ and $u_2u_3=\nu^2-T^2$ if $\nu\neq 0$, therefore we have $u_2u_3+1=\epsilon^*(T^2+1)$ and this implies the desired equality. □

We shall prove now a second lemma. In the sequel we define $f(n)$ as $3n+l-2$ for $n\geq 1$. We have the following:

Lemma 3. *Let $\alpha=[a_1,\dots,a_n,\dots]$ be an irrational element of $\mathbb{F}(3)$. We assume that for an index $n\geq 1$ we have $a_n=\lambda_nT+\mu_n$ with $(\lambda_n,\mu_n)\in\mathbb{F}_3^*\times\mathbb{F}_3$ and*

$$\alpha_n^3=\epsilon(T^2+1)\alpha_{f(n)}+z_nT+\nu_{n-1} \quad \textit{where} \quad (\epsilon,z_n,\nu_{n-1})\in(\mathbb{F}_3^*)^2\times\mathbb{F}_3.$$

We set $\nu_n=\mu_n-\nu_{n-1}$ and $\epsilon_n^*=1$ if $\nu_n=0$ or $\epsilon_n^*=-1$ if $\nu_n\neq 0$. We set $\delta_n=\lambda_n+z_n$, and $z_{n+1}=-\epsilon_n^*\delta_n$. We assume that $\delta_n\neq 0$. Then we have:

$$(a_{f(n)},a_{f(n)+1},a_{f(n)+2})=(\epsilon\lambda_nT,-\epsilon(\delta_nT+\nu_n),-\epsilon(\epsilon_n^*\delta_nT+\nu_n))$$

and

$$\alpha_{n+1}^3=\epsilon(T^2+1)\alpha_{f(n+1)}+z_{n+1}T+\nu_n.$$

Proof. We can write $\alpha_n^3=[a_n^3,\alpha_{n+1}^3]=[\lambda_nT^3+\mu_n,\alpha_{n+1}^3]$. Consequently

$$\alpha_n^3=\epsilon(T^2+1)\alpha_{f(n)}+z_nT+\nu_{n-1}$$

is equivalent to

$$\text{(7)}\quad [(\lambda_nT^3+\mu_n-z_nT-\nu_{n-1})/(\epsilon(T^2+1)),\epsilon(T^2+1)\alpha_{n+1}^3]=\alpha_{f(n)}.$$

Now we apply Lemma 2 with $U=\lambda_nT^3-z_nT+\nu_n$ and $X=\epsilon(T^2+1)\alpha_{n+1}^3$. Consequently (7) can be written as

$$\text{(8)}\qquad [\epsilon\lambda_nT,-\epsilon(\delta_nT+\nu_n),-\epsilon(\epsilon_n^*\delta_nT+\nu_n),X']=\alpha_{f(n)}$$

where

$$\text{(9)}\qquad X'=(\epsilon\alpha_{n+1}^3+\epsilon\epsilon_n^*(\delta_nT+\nu_n))/(T^2+1).$$

Moreover we have $|\alpha_{n+1}^3|\geq|T^3|$ and consequently $|X'|>1$. Thus (8) implies that the three partial quotients $a_{f(n)}$, $a_{f(n)+1}$ and $a_{f(n)+2}$ are as stated in this lemma and also that we have $X'=\alpha_{f(n+1)}$. Combining this last equality with (9), and observing that $-\epsilon_n^*\nu_n=\nu_n$, we obtain the result. □

Applying Lemma 2, we see that for a continued fraction defined by (3) and (4), the partial quotients, from the rank $l+1$ onward, can be given explicitly three by three, as long as the quantity δ_n is not zero. This is taken up in the following proposition :

Proposition 4. *Let $\alpha \in \mathbb{F}(3)$ be an infinite continued fraction expansion defined by* (3) *and* (4)*. Then there exists $N \in \mathbb{N}^* \cup \{\infty\}$ satisfying the following conditions.*
1. For $1 \le n < f(N)$, we have $a_n = \lambda_n T + \mu_n$ where $(\lambda_n, \mu_n) \in \mathbb{F}_3^* \times \mathbb{F}_3$.
2. For $1 \le n < f(N)$, define $\nu_n = \sum_{1 \le i \le n} (-1)^{n-i}\mu_i + (-1)^n \nu_0$.
Then we have

$$\mu_{f(n)} = 0 \quad \text{and} \quad \mu_{f(n)+1} = \mu_{f(n)+2} = -\epsilon\nu_n \quad \text{for} \quad 1 \le n < N.$$

3. For $1 \le n < N$, define $\epsilon_n^* = 1$ if $\nu_n = 0$ or $\epsilon_n^* = -1$ if $\nu_n \ne 0$.
Let $(\delta_n)_{1 \le n \le N}$ be the sequence defined recursively by

$$\delta_1 = \lambda_1 + \epsilon' \quad \text{and} \quad \delta_n = \lambda_n - \epsilon_{n-1}^*\delta_{n-1} \quad \text{for} \quad 2 \le n \le N.$$

Then, for $1 \le n < N$, we have

$$\lambda_{f(n)} = \epsilon\lambda_n, \quad \lambda_{f(n)+1} = -\epsilon\delta_n \quad \text{and} \quad \lambda_{f(n)+2} = -\epsilon\epsilon_n^*\delta_n.$$

Proof. Starting from (4), since $f(1) = l+1$, setting $\epsilon' = z_1$ and observing that all the partial quotients are of degree 1, we can apply repeatedly Lemma 3 as long as we have $\delta_n \ne 0$. If δ_n happens to vanish, the process is stopped and we denote by N the first index such that $\delta_N = 0$, otherwise N is ∞. The formula $\nu_n = \mu_n - \nu_{n-1}$, implies clearly the equality for ν_n. From the formulas $\delta_n = \lambda_n + z_n$ and $z_{n+1} = -\epsilon_n^*\delta_n$ for $n \ge 1$, we obtain the recursive formulas for the sequence δ. Finally the formulas concerning μ and λ are directly derived from the three partial quotients $a_{f(n)}$, $a_{f(n)+1}$ and $a_{f(n)+2}$ given in Lemma 3. □

• *Last step of the proof:* We start from the element $\beta \in \mathbb{F}(3)$, introduced in the first step of the proof, defined by its l first partial quotients, where $l = k_m + 1$, and by (4) with $(\epsilon, \epsilon', \nu_0) = ((-1)^m, 1, 1)$. According to the first step of the proof, we need to show that $\beta = \omega(m, \boldsymbol{\eta}, \mathbf{k})$. To do so, we apply Proposition 4 to β, and we show that $N = \infty$ and that the resulting sequences $(\lambda_n)_{n\ge1}$ and $(\mu_n)_{n\ge1}$ are the one which are described in the theorem.

From the definition of the l-tuple $(\mu_1, \dots, \mu_l)$ and $\nu_o = 1$, we obtain

(10)
$$\nu_t = \eta_i \quad \text{if} \quad t = t_{i,0} \quad \text{and} \quad \nu_t = 0 \quad \text{otherwise}, \quad \text{for} \quad 1 \le t \le l.$$

Since $\mu_{f(n)+1} = \mu_{f(n)+2}$, we have $\nu_{f(n)+2} = \nu_{f(n)}$. Since $\mu_{f(n)} = 0$, we also have $\nu_{f(n)} = -\nu_{f(n)-1} = -\nu_{f(n-1)+2}$. This implies $\nu_{f(n)+2} =$

$(-1)^{n-1}\nu_{f(1)+2}$. Since $\nu_{f(1)+2} = \nu_{f(1)} = -\nu_{f(1)-1} = -\nu_l = 0$, we obtain

$$\nu_{f(n)} = \nu_{f(n)+2} = 0 \quad \text{for} \quad 1 \leq n < N. \tag{11}$$

Moreover, from $\nu_{f(n)+1} = \mu_{f(n)+1} - \nu_{f(n)}$ and (11), we also get

$$\nu_{f(n)+1} = -\epsilon\nu_n \quad \text{for} \quad 1 \leq n < N. \tag{12}$$

Now, it is easy to check that we have $f(t_{i,n}) + 1 = t_{i,n+1}$. Since $\epsilon = (-1)^m$, (12) implies $\nu_{t_{i,n}} = (-1)^{m+1}\nu_{t_{i,n-1}}$ if $t_{i,n} < f(N)$. By induction from (10), with (11) and (12), we obtain

$$\nu_{t_{i,n}} = (-1)^{(m+1)n}\eta_i \quad \text{and} \quad \nu_t = 0 \text{ if } t \neq t_{i,n}, \text{ for} \quad 1 \leq t < f(N). \tag{13}$$

Since we have $\mu_n = \nu_n + \nu_{n-1}$, from (11) and $\nu_0 = 1$, we see that μ_n satisfies the formulas given in the theorem, for $1 \leq n < f(N)$. Moreover, (13) implies clearly the following:

$$\epsilon_t^* = \begin{cases} -1 & \text{if } t = t_{i,n}, \\ 1 & \text{otherwise} \end{cases} \quad \text{for} \quad 1 \leq t < f(N). \tag{14}$$

Now we turn to the definition of the sequence $(\lambda_n)_{n\geq 1}$ given in the theorem, corresponding to the element ω. With our notations and according to (14), we observe that this definition can be translated into the following formulas

$$\lambda_1 = 1 \quad \text{and} \quad \lambda_n = \epsilon_{n-1}^*\lambda_{n-1} \quad \text{for} \quad 2 \leq n < f(N). \tag{15}$$

Consequently, to complete the proof, we need to establish that $N = \infty$ and that (15) holds. The recurrence relation binding the sequences δ and λ , introduced in Proposition 4, can be written as

$$\delta_n + \lambda_n = -\epsilon_{n-1}^*(\delta_{n-1} + \lambda_{n-1}) + \epsilon_{n-1}^*\lambda_{n-1} - \lambda_n \quad \text{for} \quad 2 \leq n \leq N. \tag{16}$$

Comparing (15) and (16), we see that $\delta_n + \lambda_n = 0$, for $n \geq 1$, will imply that δ_n never vanishes, i.e. $N = \infty$, and that the sequence $(\lambda_n)_{n\geq 1}$ is the one which is described in the theorem. So we only need to prove that $\delta = -\lambda$. Since β and ω have the same first partial quotients, (15) holds for $2 \leq n \leq l$. Since $\delta_1 = \lambda_1 + \epsilon' = -1 = -\lambda_1$, combining (15) and (16), we obtain $\delta_n = -\lambda_n$ for $1 \leq n \leq l$. We also have, by Proposition 4, $\lambda_{l+1} = \lambda_{f(1)} = \epsilon\lambda_1 = (-1)^m = \lambda_l$, and therefore we get $\delta_{l+1} = \lambda_{l+1} - \epsilon_l^*\delta_l = \lambda_{l+1} + \lambda_l = -\lambda_{l+1}$. By induction, we shall now prove that $\delta_t = -\lambda_t$ for $t = f(n)+1, f(n)+2$ anf $f(n+1)$ with $n \geq 1$. From (11) and (12), we have $\epsilon_{f(n)}^* = \epsilon_{f(n)+2}^* = 1$ and $\epsilon_{f(n)+1}^* = \epsilon_n^*$. Thus we get, using Proposition 4 :

$$\delta_{f(n)+1} = \lambda_{f(n)+1} - \epsilon^*_{f(n)}\delta_{f(n)} = \lambda_{f(n)+1} + \lambda_{f(n)} = -\epsilon\delta_n + \epsilon\lambda_n = -\lambda_{f(n)+1}.$$

$$\delta_{f(n)+2} = \lambda_{f(n)+2} - \epsilon^*_{f(n)+1}\delta_{f(n)+1} = \lambda_{f(n)+2} + \epsilon^*_n\lambda_{f(n)+1} = -\lambda_{f(n)+2}.$$

$$\delta_{f(n+1)} = \lambda_{f(n+1)} - \epsilon^*_{f(n)+2}\delta_{f(n)+2} = \epsilon\lambda_{n+1} + \lambda_{f(n)+2} = \epsilon(\lambda_{n+1} - \epsilon^*_n\delta_n)$$
$$= \epsilon\delta_{n+1} = -\epsilon\lambda_{n+1} = -\lambda_{f(n+1)}.$$

So the proof of the theorem is complete.

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